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Enhanced nitrogen removal under low-temperature and high-load conditions by optimization of the operating modes and control parameters in the CAST system for municipal wastewater

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ABSTRACT

Sequencing batch reactor (SBR) technology has become one of the commonly used treatment systems for municipal and industrial wastewater in the past decades. Cyclic activated sludge technology is one of the newly developed variations of SBR process. In this study, because the water quality situation of effluent under low-temperature and high-load conditions was unstable in Wang-hill Wastewater treatment plant, and the phenomena of exceeding discharge standard about ammonia-nitrogen (NH_3-N) and total nitrogen (TN) were serious in winter, the different operation modes (operation cycle and aeration time) and control parameters were selected and optimized to improve nitrogen removal performance, respectively. The results indicated that the national first level *B* criteria of the effluent quality could be reached and the stable discharge could be achieved under the operation conditions of the *C* mode with 6 h per cycle [influent 2 h, aeration 2.5 h (aeration starting from 1.5 h after influent), settling 1 h, draw/idle 1 h], the average removal rates of chemical oxygen demand (CODcr), NH_3-N, and TN in the reactor were 91.8, 75.6, and 62.9%, respectively. Furthermore, the dissolved oxygen (DO) level and mixed liquor suspended solids (MLSS) content in the aeration phase were both optimized on the basis of the preferred *C* mode. The best ranges of DO and MLSS concentration during the aeration phase as high as 2.0–3.0 mg/L and 5,000–6,000 mg/L are essential for the best nitrogen removal performance. The average removal rates of CODcr, NH_3-N, and TN in the reactor were 90.3, 83.2, and 69.1%, respectively. Obviously, alternating operation mode combined with parameter optimization was the optimal nitrogen removal strategy for low-temperature and high-load wastewater. These data are of great practical significance for the scientific control and management of the wastewater treatment plant and for references of water engineering professionals.

Keywords: Nitrogen removal; Operation mode; Municipal wastewater; Cyclic activated sludge technology; Optimization

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1. Introduction

Nutrient removal is the basic requirement for wastewater treatment with the implementation of high discharge standard of treated water. Nitrogen is one of the key nutrients causing eutrophication in water body, which is required to be removed from water resources in many countries. Wastewater treatment has been a challenge throughout the years due to varying influent chemical and physical characteristics and stringent effluent regulations. Treatment systems using activated sludge have been able to handle many of these difficulties. Sequencing batch reactor (SBR) is a popular activated sludge process and both municipal and industrial wastewater has been successfully treated in SBR systems. One of the benefits of using SBR treatment is that effluent quality can meet current and anticipated future nitrogen requirements for surface discharge. The use of batch processes for treating wastewater is not a recent development, batch processes have been in development and use since the turn of the twentieth century. As early as 1914, Aderm and Lockett in the UK invented the activated sludge treatment technology of intermittent flow, and it was directly applied to Salford City sewage treatment [1]. However, facility design gradually moved to continuous flow or "conventional" activated sludge systems after 1920 due to the high degree of operator attention and automation required for SBR. The clogging of air diffusers (aeration) caused by periodic settling of sludge on the air diffusion systems in SBRs also increased the complexity of their operation. In the early 1960s, interest was revived in batch systems with the development of new technology and equipment, most significantly the micro-processor. In addition, improvements in aeration devices and automatic control systems have allowed the development of the "fill-and-draw" systems to their present level of efficiency and now enable SBR to successfully compete with, and in most cases outperform, conventional activated sludge systems [2]. The SBR has received considerable attention since Irvine and Davis [3] described its operation. In 1979, Irvine and Busch had decisively laid theoretical basis for intermittent activated sludge process, and studies of SBR process were originally conducted at University of Notre Dame, Indiana, United States [4–6], and afterward this activated sludge process of the intermittent influent and effluent was known as SBR. There is one important difference between the SBR and conventional activated sludge systems. The processes in the conventional plant are carried out simultaneously in separate tanks; whereas, in the SBR process, treatment takes place sequentially in a common "reactor" tank. The reactor in an SBR system has five basic operating modes. Listed sequentially in the treatment process, they are (1) fill, (2) react, (3) settle, (4) draw, and (5) idle. These modes of the SBR are controlled by time to achieve the effluent quality and treatment capacity objectives. SBR had very clear advantages compared with conventional activated sludge system [7]. A major advantage of the SBR system compared to the conventional system is its flexibility to adapt and modify reactor conditions through time controls or dissolved oxygen settings during the operational phases. The computer controls allow the operator the ability to change the effective size/volume of the aeration, anoxic, and clarification processes to achieve effluent goals. This allows SBR facilities to adapt to changing influent loading conditions and consistently maintain the objective effluent quality.

As a variation of SBR process, the processing performance of the cyclic activated sludge technology (CAST) will not only inherit SBR characteristics of strong resistance to high load and flexible operational modes, but also further strengthen the performance of nitrogen and phosphorus removal, it can also well mitigate the impacts of water quality, water quantity, and toxic substances [8–11]. Therefore, CAST process has good effects for nitrogen and phosphorus removal and it is not easy to produce sludge bulking, the operation cycle is not long, and the volume of sewage treatment is large, it has a wide range of applications for the treatment of municipal sewage [12–14]. CAST also has features of low cost in infrastructure and convenient operation in management, this process has also been widely used in China in recent years. But, the application of CAST technology in China is still at the exploration stage [15]. Based on the previous operation situations in Wang-hill wastewater treatment plant (WWTP), we found that the CAST process had good removal effects for chemical oxygen demand (CODcr), biochemical oxygen demand after 5 days (BOD_5), suspended solids (SS), total nitrogen (TN), total phosphorus (TP), and ammonia-nitrogen (NH_3-N) under the conditions of normal temperature (18℃–30℃). However, the TN removal efficiency was relatively low and the effluent quality of TN was unstable at low temperature in winter (10℃–18℃), the phenomena of NH_3-N and TN exceeding standards were serious. Furthermore, the time from December 2007 to March 2008 was coincided with the continuous cold weather in Chongqing, the influent temperature is only 10℃–18℃ in December 2007 in WWTP, and the water temperatures in most days were all below 15℃. In general, low temperature is not conducive to nitrification reaction [16–18], so the concentration of nitrate- and nitrite-nitrogen (NO_3-N and NO_2-N) required for denitrification decreases, and the effluent concentrations of NH_3-N and organic nitrogen (ON) increases, thus it affects nitrogen removal performance of the system. Besides, the conventional process of nitrification and denitrification is hampered by the low removal efficiency and the high energy consumption for aeration [19]. The operating modes and control parameters are the two important aspects affecting the treatment performance [20–24], according to the process characteristics and the problems during pre-operation for the WWTP, it is necessary and urgent for the optimization studies of operating modes and control parameters under the low-temperature and high-load conditions in order to achieve the enhanced effects of nitrogen removal in WWTP. Therefore, the objective of this study is to explore and develop stable operation systems by the optimization of operating modes and control parameters under the low-temperature and high-load conditions, and to enhance the nitrogen removal performance of CAST system and ensure effluent quality, the results can also provide references for other municipal wastewater treatment plant.

Table 1
Designed indexes of the influent quality and allowable First level *B* criteria of the effluent quality

Water quality item	Designed influent (mg/L)	First level *B* criteria of effluent[a] (mg/L)
COD	360	60
BOD_5	180	20
SS	220	20
NH_3-N	35	8 (15)[b]
TN	40	20
TP	5	1.0 (1.5)[c]

[a]National first level *B* criteria' (GB18918-2002) of effluent is implemented when the discharged water from municipal wastewater treatment plant flows into GB 3838 Grade III level of surface water (suitable for centralized drinking water, surface water source protection zones, general fish protection areas, and swimming areas; in this standard, with the exception of centralized drinking water source protection zones, and swimming areas), GB 3097 Grade II level of seawater, lake and reservoir etc close or half-close water area.
[b]The outside value of bracket is the control index for water temperature >12℃, the inside value of bracket is the control index for water temperature ≤12℃.
[c]The outside value of bracket denotes that the project is built after January 1, 2006; the inside value of bracket denotes that the project is built before December 31, 2005.

2. Materials and methods

2.1. General situation of project

2.1.1. The designed water quantity and water quality

WWTP covers an area of 45.3 acres with a total designed treatment capacity of $5 \times 10^4\,m^3/d$, its construction of the initial phase serves the number of population of 150,000 and the total designed treatment capacity of the initial project is $2 \times 10^4\,m^3/d$. The project was completed and put into use in March 2007. The CAST reactor is the main reactor, the processes are biological nitrogen and phosphorus removal supplemented with chemical methods, the tail water discharge is implemented by the “National first level *B* criteria” specified in the “Discharge standard of pollutants for municipal wastewater treatment plant” (GB18918-2002) [25]. This standard stated the pollutants limited value of effluent, exhaust emission, and sludge disposition (control) in municipal wastewater treatment plant, this standard is suitable for the management of effluent, exhaust emission, and sludge

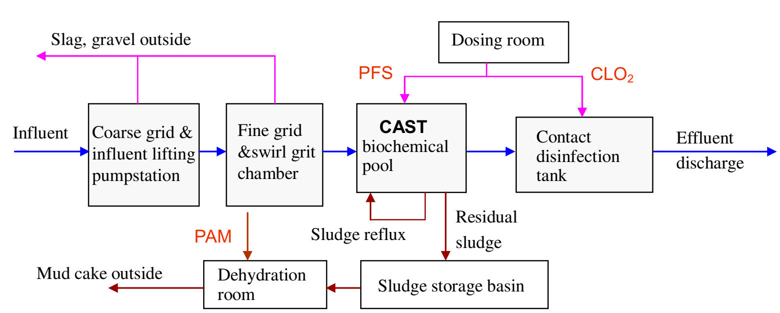

Fig. 1. Flow chart of treatment process of CAST (PFS: Poly Ferric Sulfate; PAM: Polyacrylamide; ClO_2: chlorine dioxide). Notes: PFS is used as reagent dosing for the chemical phosphorus removal, the dosage point lies in the center of biological selection zone of CAST biochemical pool; ClO_2 is used reagent dosing for the disinfection of contact tank; PAM is the organic polymer flocculant used for the sludge dewatering, the dosage is 4 kg (PAM) powder/ton dry sludge.

disposition (control) in municipal wastewater treatment plant. The monitoring analytical procedures in this standard were executed by "Standard Analytic Methods for the Examination of Water and Wastewater" promulgated by State Environmental Protection Administration [26]. The designed indexes of the influent quality and allowable First level *B* criteria of the effluent quality (Daily value, First level *B* criteria) are shown in Table 1.

2.1.2. The actual water quantity and water quality

The seasonal changes of the influent in WWTP are obvious. The daily average water quantity in winter (December 2007 to February 2008) was about 1 × 10^4 m^3, but in summer (June to August 2008) was more than 1.6 × 10^4 m^3, it is higher than other seasons, the changing range of water quantity during the winter and summer period reached 60%. Besides, the actual changing situations of influent quality during the study period in winter are the following: the concentration of pollutants in summer and autumn was low, the average influent concentration of CODcr was only about 50% of the designed value, the average concentration of BOD_5 was 35–50% of the designed value, the average concentrations of NH_3-N and TN were 60 and 70% of the designed values, respectively. However, the concentration of all pollutants were generally higher in winter and spring, the average influent concentration of CODcr reached 70–90% of the design value, the average concentration of BOD_5 reached 65–114% of the designed value, NH_3-N and TN concentrations respectively reached 60–77 and 92–121% of designed values. The low concentration of pollutants in summer and autumn was closely related to the pollutant dilution due to abundant rainfall in these seasons and the increased water consumption during high temperature period. The influent concentration of pollutants during low temperature in winter will cause impacts on the stable operation of the CAST system.

2.1.3. Flow chart of treatment process

Fig. 1 represents the specific CAST process in WWTP. Sewage enters into the plant from municipal wastewater pipe network, and it flows in turn the coarse grid, sewage lifting pump station, the fine grid, then it is upgraded to the swirl grit chamber to remove impurities and sands, afterwards it enters into the CAST biochemical pool, through the water decanter, it is decanted into contact disinfectant tank, then it is discharged into the Xiao-Zi River by the drainage pump station and eventually enters into the Yangtze River. Sludge thickening is carried out for excessive sludge in storage basins, and it is dewatered through the sludge dewatering machine in dehydration room.

Table 2
Main design parameters and values of the Cyclic Activated Sludge Technology (CAST) process

Design parameters	Values
CAST dimensions (length × width × height/m)	30 × 18 × 6.8
Effective water depth (m)	5.8
Volume of biological selection zone (m^3)	282
Volume of main reaction zone (m^3)	2,850
Maximum draw height (m)	1.6
Water filling ratio	0.2–0.28
Sludge retention time (SRT) (d)	18
Hydraulic retention time (HRT) (h)	14
Operation time per cycle (h)	4
Aeration time (h)	2
Settling time (h)	1
Draw time (h)	1
Number of cycles per day	6
MLSS (mg/L)	3,500–5,500
DO (mg/L)	2.0–3.0
Sludge reflux ratio	20%

[a]Flygt Diving Stirrers (No. SR4630), a product of ITT (International Telephone and Telegraph Corporation) Corporation, Stockholm, Sweden.
[b]Water Decanter is from Hangzhou Sudi Environmental Protecting Industrial CO., Ltd., NO. 398, dengyun Road, Hangzhou, China. http://www.hzshdi.com/www.hzsudi.cn.
[c]Roots Blower is from Shandong Jinhaosanyang Environmental Protection Machine Co., Ltd., China. http://www.jinhaosanyang1.com.

2.1.4. Main facilities, equipments and design parameters

The initial project of CAST biochemical pool was designed as 2 × 10^4 m^3/d, it was divided into two groups and four pools, the capacity of single pool was 5,000 m^3/d. Main design parameters are in Table 2.

To make the return sludge and wastewater mix sufficiently, the biological selection zone was equipped with two sets of ITT Flygt Diving Stirrers[a] (underwater mixers), this agitator belongs to types of the high rev (705 rpm) and small impeller (370 mm), it has better mixing effects. The main reaction area is equipped with a sludge recycle pump, it will make the sludge of the main reaction zone return to the biological selection zone, operation parameters: Q = 85 m^3/h, H = 3.5 m, pump power 3 kW. Residual sludge will be pumped into storage basins through a residual sludge pump, operation parameters: Q = 60 m^3/h, H = 7.8 m, pump power 3 kW. In addition, draw or decant phase is the withdrawal phase to discharge the clarified effluent from the reactor. The most fundamental characteristic of the SBR process is that the drainage forms of single reactors are all still settling and centralized drainage, the water level of the drainage pool is changing. The purpose of settling mode is to allow solids separation to occur, which provides a clarified supernatant to be discharged as effluent. So the use of a water decanter with the water level changes was required in order to ensure the drainage without disturbance to the aqueous layer and the supernatant water always at the top level, and finally to achieve the ultimate goal of continuous sewage treatment.

The withdrawal mechanism should be designed and operated in a manner that prevents floating matter from being discharged, so two sets of SHB-650 type rotary decanter[b] were selected as the withdrawal mechanism in one biochemical pool. The processing capacity is 620–650 m^3/h for one-set rotary decanter, the power is 1.1 kW, the electricity use is 0.0017 kWh/ton sewage, the largest decanting depth is 3.5 m, the time for draw phase is one hour which ranges from 5% to more than 30% of the total cycle time, it is consistent with the design requirements. The biological selection zone and the main reaction area of the CAST biochemical pool are shown in Fig. 2(a) and (b). Roots blower[c] is one of the key facilities to ensure normal working of aeration system, the maximum gas supply capacity of blower housing is 113.7 m^3/min through calculation, it can satisfy the requirements for 40,000 m^3 at a specified future date. The total number of roots blower in this project is 3 sets, two sets are used with one standby, two sets are designed with frequency conversion and can automatically adjust the volume of gas supply. Single wind quantity: 56.85 m^3/min, pressure: 70 kPp, power: 110 kW, rotation speed: 1,490 rps.

2.2. Sampling and analysis methods

The whole optimization process under low-temperature and high-load conditions was divided into two stages from December 2007 to March 2008, first was the optimization study of operating modes under low-temperature conditions from December 2007 to January 2008, second was the optimization study of important control parameters under the preferred operating mode from January 2008 to March 2008. Average daily samples of influent and effluent wastewater were formed from samples collected by the automatic sampler once per hour, and the hourly samples were used for the 24-h composite of equal volume. The sampling site for influent lay in the fine grille, the sampling point for effluent was located at the front of the contact disinfectant tank, more importantly, the actual sampling position was placed for the center of sampling section and 1/4 depth of surface. In addition, the sampling point about cycle changes of pollutants in Section 3.2 was placed in the centrally fixed position of CAST biochemical pool, the sampling started from 0 min, and the sampling frequency was once each 30 min. Daily water samples after pre-processing were stored in the refrigerator with 4℃, and the unified mensuration started after the completion of the whole day sampling within the storage life. The daily samples were analyzed in accordance with methods presented in "Standard Analytic Methods for the Examination of Water and Wastewater"[26]. The contents of this book version mainly include five chapters: the synopses of water pollution and monitoring techniques, quality control and quality guarantee, compositive indexes and inorganic matter, organic matter, and the biological monitoring method of water and wastewater. Wastewater characteristics which were monitored in the study included CODcr, NH_3-N, TN, DO, mixed-liquor suspended solids (MLSS), NO_2-N, NO_3-N and water temperature; other characteristics, including BOD_5, TP, pH, SS, MLVSS, Sludge settling

Fig. 2. (a) The biological selection zone and (b) the main reaction area of the CAST biochemical pool.

ratio, and the biological phase of sludge were tested in the WWTP operation. Testing items and monitoring methods are identified in Table 3.

2.3. The design of operational modes during the low temperature period

The biochemical treatment under low-temperature and high-load conditions is always a difficult problem and extremely unfavorable [27–29]. The designed operating mode was used in WWTP during the pre-production operation period. However, along with the dropping water temperature and the rising concentration of pollutants in winter, the processing performance of the system gradually reduced to be greater than the discharge standard, especially nitrogen removal performance had more obvious decrease, the exceeded standard phenomenon of the effluent NH_3-N and TN changed more and more serious. There were many factors that affecting nitrogen removal for the CAST process, which included operation modes (operation cycle and aeration time), water temperature, DO, MLSS, sludge retention time (SRT), C/N ratio, reflux ratio, etc. where the three factors of the operation mode, DO and sludge concentrations could be directly regulated and modified during operation. Because the actual water quantity is about 10 000 m^3/d during the winter in WWTP, it is only 1/2 of the designed scale, it is necessary to regular the operating cycles appropriately, thus prolonging the aeration time and changing the aeration mode are selected as the main method to enhance denitrification effects of the system. During the low temperature in winter, the following three kinds of operating procedures were carried out in WWTP (Table 4).

"A mode" is the designed operating mode with 6 cycles per day (4 h per cycle), it is the non-restrictive aeration with the total 2 h time of influent and aeration, while the procedures of *B* and *C* mode are both 4 cycles (6 h per cycle), three biochemical pools are alternately used to run in order to ensure the continuous influent, single pool runs 4 cycles per day. The aeration time of *B* mode is still 2 h, but the aeration mode is changed into restrictive aeration, it means that the aeration time is after the influent completion. However, the aeration time of *C* mode will be extended to 2.5 h, the aeration method is the semi-restrictive aeration, the aeration starts from the 90 min influent, the frontal 30 min are micro aeration, and the latter 2 h are normal aeration. Although the operating modes are different, the other operating conditions are

Table 3
Items and methods of monitoring analysis from "standard analytic methods for the examination of water and wastewater"

Testing items	Monitoring method
CODcr	Potassium dichromate method
BOD_5	HACH BOD TrakTM Ⅱtester
TN	Potassium persulfate digestion- UV spectrophotometric method
NH_3-N	Pre-distillation, Nessler's reagent photometry
NO_3-N	Phenol disulfonic acid spectrophotometric
NO_2-N	N-(1-naghthyl)-1,2-diaminoethane dihydrochloride spectrophotometry
TP	Potassium persulfate digestion-ammonium molybdate spectrophotometric method
pH	HACH portable pH meter (senION+PH1)
Sludge settling ratio (SV%)	100 mL cylinder measurement
SS, MLSS, MLVSS	Weight method
DO, water temperature	HACH portable dissolved oxygen analyzer
Biological phase of sludge	Optical microscope

Notes: HACH, global leader in water quality testing and water quality analysis, offers portable, laboratory and on-line instruments for testing vital water quality parameters; SS, suspended solid; MLVSS, mixed liquor volatile SS; pH, hydrogen ion concentration.

Table 4
The contrast of different operating modes (*A*, *B*, and *C*) under low-temperature and high-load conditions in WWTP

	Stage				
Mode	Influent (min)	Aeration (reaction) (min)	Settling (min)	Draw/ idle (min)	Aeration mode
A (4 h)	120		60	60	Non-restrictive aeration
B (6 h)	120	120	60	60	Restrictive aeration
C (6 h)	120	120 (Aeration after 90 min of influent)	60	60	Semi-restrictive aeration

Notes: The aeration time of *C* mode starts from 90 min of influent, the total aeration time is 150 min, the time per cycle is 6 h, and 4 cycles per day.

basically the same as designs, DO is maintained at 2.0–4.0 mg/L, MLSS is at 3,500–4,500 mg/L, water-filled ratio is from 0.2 to 0.28, SRT is at 18–24 d, and water temperatures of the three operating modes are at 10–18, 8–16, and 7–16℃, respectively.

3. Results and discussion

3.1. The optimization of operation modes

3.1.1. The analysis of CODcr removal effects

The CODcr is determined by potassium dichromate method which has high oxidation rate and good reproducibility, this method is commonly applied to determine the total amount of organic matter in water samples. CODcr removal effects of three operation modes are as shown in Fig. 3 and Table 5. The influent COD_{Cr} of *A* mode is 154–493 mg/L with an average of 284 mg/L during regulation; the effluent COD_{Cr} is 20.3–41.7 mg/L with an average of 30.46 mg/L, the removal rate is 83.1–92.0%, and the average value which is calculated by average influent and effluent is 88.4%. The influent COD_{Cr} of *B* mode is 160–527 mg/L with an average of 301 mg/L; the effluent COD_{Cr} is 22.2–34.8 mg/L with an average of 26.5 mg/L, the removal rate is 84.8–94.8% with an average of 90.32%. The influent COD_{Cr} of *C* mode is 260–455 mg/L with an average of 349 mg/L; the effluent COD_{Cr} is 17.9–36.7 mg/L with an average of 27.4 mg/L, the removal rate is 88.2–95.8% with an average of 91.8%.

Fig. 3 indicates that the effluent COD_{Cr} concentration about three kinds of the operating modes during low-temperature period can stabilize up to the "National first level *B* criteria". Although the average influent concentration of *C* mode is the maximum value, the average effluent concentration is the minimum value, the removal efficiency of *C* mode is also better than *A* and *B* modes. This is because the aeration time of *C* mode is longer than *A* and *B* modes, the prolonged aeration time is a benefit for further degradation of organic matter. The aeration times of *A* mode and *B* mode are both 2 h, but the *B* mode uses the restrictive aeration mode, it tends to be the plug-flow type reactor, the organic load ratio (Food/Micro-organism, F/M) of the reaction process is bigger than *A* mode, it will help to remove refractory organics in wastewater. The *C* mode takes more favorable and flexible semi-restrictive aeration manner, so *C* mode can obtain a better CODcr removal effects than *A* and *B* modes.

3.1.2. The analysis of NH_3-N removal effects

The NH_3-N removal efficiency of three operating modes is shown in Fig. 4 and Table 5. The influent concentration of NH_3-N for *A* mode is 16.2–28.2 mg/L with an average of 20.3 mg/L during regulation. The influent NH_3-N concentration of *B* mode is 17.3–28.1 mg/L with an average of 22.2 mg/L. The influent NH_3-N of *C* mode is 16.9–28.9 mg/L with an average of 22.7 mg/L. However, there are big differences for NH_3-N effluent concentration of the three modes, the effluent concentration of NH_3-N for *A* mode is 7.1–13.7 mg/L with an average of 9.4 mg/L; the effluent concentration of NH_3-N for *B* mode is 5.2–11.4 mg/L with an average of 8.1 mg/L; the effluent concentration of NH_3-N for *C* mode is 4.2–6.9 mg/L with an average of 5.4 mg/L, NH_3-N removal effects of *C* mode are the best. For the removal efficiency, NH_3-N removal rate of *A* mode is 48.4–59.0% with an average of 53.8%; NH_3-N removal rate of *B* mode is 57.8–69.9% with an average of 63.7%; NH_3-N removal rate of *C* mode is 69.6–79.4% with an average of 75.6%.

Fig. 4 also shows that there are big differences of NH_3-N removal effects under three operational modes. The proliferation speed of the nitrobacteria slows down under the conditions of low temperature in winter, its activity changes poor, and thus the nitrification ability and NH_3-N removal rate of the system decrease. NH_3-N removal efficiency of *C* mode is better than *A* and *B* modes by prolonging the aeration time and changing aeration method. In general,

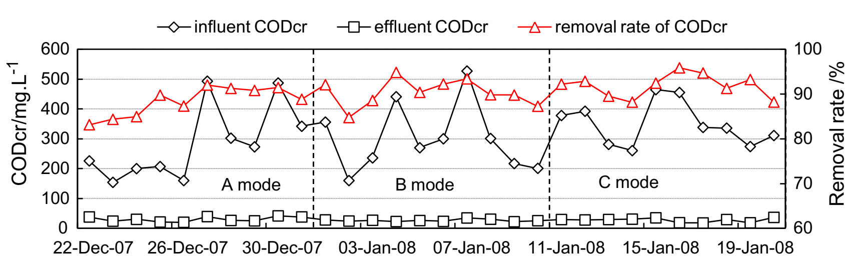

Fig. 3. The comparison of COD removal performance under low-temperature and different operation modes.

Table 5
Comparisons of CODcr, NH_3-N, and TN removal performance under low temperature and different operation modes

Modes	Date (D/M/Y)	Influent (mg/L)			Effluent (mg/L)			Removal rate (%)		
		CODcr	NH_3-N	TN	CODcr	NH_3-N	TN	CODcr	NH_3-N	TN
A	22/12/07	226	16.9	29.8	38.1	7.1	18.6	83.1	58.0	37.6
	23/12/07	154	19.1	33.3	24.1	8.6	20.4	84.4	55.0	38.7
	24/12/07	200	18.2	37.2	30.1	9.4	19.4	85.0	48.4	47.8
	25/12/07	207	17.0	39.6	21.2	7.5	20.4	89.8	55.9	48.5
	26/12/07	160	16.6	28.6	20.3	7.6	17.8	87.3	54.2	37.8
	27/12/07	493	16.5	39.0	39.4	8.0	23.6	92.0	51.3	39.5
	28/12/07	302	27.0	48.7	26.4	12.6	26.1	91.3	53.3	46.4
	29/12/07	273	28.2	62.4	25.1	13.7	28.6	90.8	51.4	54.2
	30/12/07	487	24.9	52.7	41.7	10.2	25.6	91.4	59.0	51.4
	31/12/07	342	18.7	49.4	38.2	9.1	23.7	88.8	51.3	52.0
	Average	284	20.3	42.1	30.5	9.4	22.4	88.4	53.8	45.4
B	01/01/08	356	23.6	63.9	28.2	9.2	26.4	92.1	61.0	58.7
	02/01/08	160	24.1	32.0	24.4	8.9	16.2	84.8	63.1	49.4
	03/01/08	236	19.3	37.8	27.0	6.4	15.6	88.6	66.8	58.7
	04/01/08	441	28.1	44.1	22.8	11.4	20.4	94.8	59.4	53.7
	05/01/08	270	24.8	35.7	26.0	10.5	18.3	90.4	57.8	48.7
	06/01/08	300	18.2	50.1	23.3	6.6	24.9	92.2	63.7	50.3
	07/01/08	527	17.3	52.9	34.8	5.2	22.3	93.4	69.9	57.8
	08/01/08	301	24.7	39.2	30.6	7.9	18.1	89.8	68.0	53.8
	09/01/08	217	17.8	44.6	22.2	6.1	20.4	89.8	65.7	54.3
	10/01/08	201	23.6	41.5	25.6	9.1	22.8	87.3	61.4	45.1
	Average	301	22.2	44.2	26.5	8.1	20.5	90.3	63.7	53.1
C	11/01/08	378	28.8	50.8	29.5	6.4	18.7	92.2	77.7	63.2
	12/01/08	392	23.9	49.4	28.1	5.8	17.3	92.8	75.7	65.0
	13/01/08	281	17.5	35.3	29.5	5.3	16.4	89.5	69.6	54.0
	14/01/08	260	20.2	44.0	30.7	4.2	18.9	88.2	79.2	57.1
	15/01/08	465	16.9	54.9	35.2	4.8	18.5	92.4	71.6	66.4
	16/01/08	455	28.9	55.8	18.9	6.9	18.7	95.8	76.1	66.5
	17/01/08	338	22.6	48.3	17.9	5.6	15.7	94.7	75.2	67.5
	18/01/08	336	21.4	38.7	29.4	4.8	16.6	91.3	77.6	57.1
	19/01/08	274	18.1	45.9	18.5	4.7	14.2	93.2	74.0	69.2
	20/01/08	311	28.3	46.3	36.7	5.8	16.9	88.2	79.4	63.4
	Average	349	22.7	46.9	27.4	5.4	17.2	91.8	75.6	62.9

NH_3-N can be removed by the aerobic reaction, the nitrification reaction is complete by the long aerobic time. The aeration time of *A* mode and *B* mode are both 2 h, but the *B* mode uses restrictive aeration mode, it is equivalent to the extension of the aerobic time, so the nitrification effect is better than *A* mode, while *C* mode can achieve best effects of nitrification due to its semi-restrictive aeration mode.

3.1.3. The analysis of the TN removal effects

The TN removal efficiency under three operation modes is shown in Fig. 5 and Table 5. The influent TN concentration of *A* mode is 28.6–62.4 mg/L with an average of 42.1 mg/L during regulation; the influent TN of *B* mode is 32.0–63.9 mg/L with an average of 44.2 mg/L; the influent TN of *C* mode is 35.3–55.8 mg/L with an average of 46.9 mg/L. However, TN effluent concentration of the three modes has large difference, the effluent TN of *A* mode is 17.8–28.6 mg/L with an average of 22.4 mg/L; the effluent TN of *B* mode is 15.6–26.4 mg/L with an average of 20.5 mg/L; the effluent TN of *C* mode is 14.2–18.9 mg/L with an average of 17.2 mg/L, in addition to *C* mode, the *B* and *C* modes both have the phenomenon of exceeded standard (20 mg/L). For the removal efficiency, TN removal rate of *A* mode is 37.6–54.2% with an average of 45.4%; TN removal rate of *B* mode is 45.1–58.7% with an average of 53.1%; TN removal rate of *C* mode is 54.0–69.2% with an average of 62.9%.

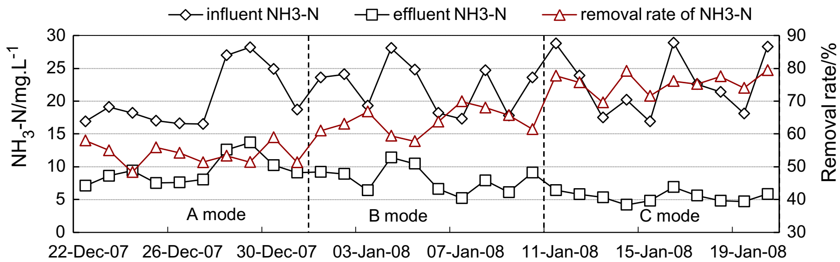

Fig. 4. The comparison of NH_3-N removal performance under low-temperature and different operation modes.

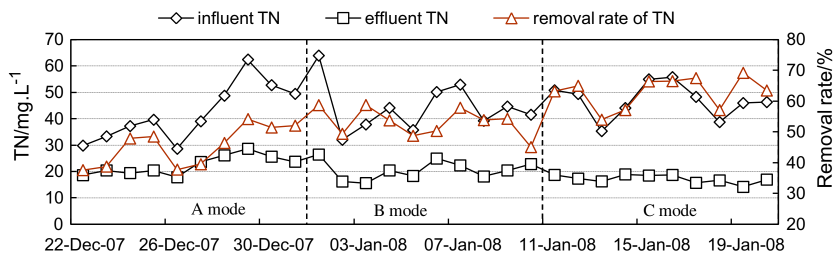

Fig. 5. The comparison of TN removal performance under low-temperature and different operation modes.

The TN removal effects of three operation modes are very different, the TN removal efficiencies of *B* and *C* modes are superior to *A* mode, reasons are primarily the following aspects: (1) The non-aeration time of *B* and *C* mode is longer than *A* mode, thus the *denitrobacteria* in the non-aeration phase can take full advantage of the slow-speed biodegradable substances and intracellular carbonaceous materials deposited in endo-microorganisms for endogenesis denitrification [30], these substances include glycogen, poly-β-hydroxy butyric acid (PHB) and the carbon substances produced by cell decomposition, so the denitrification effect is enhanced. (2) Meanwhile, the reflux time of *B* and *C* modes within a reaction cycle is longer and they have a higher reflux ratio than *A* mode. The aeration and mixture reflux for *A* mode occur at the same time, the reflux time is 2 h, the reflux volume accounts for 20% of the total influent quantity, while the reflux time of the *B* and *C* modes during influent and aeration period is 4 h, the reflux volume is equivalent to 2 times than *A* mode, high reflux volume means that the total denitrification amount occurred in the biological selection area increases gradually, so nitrogen removal efficiency of the system can be improved on the basis of this theory. Alternatively, it also can be seen that nitrogen removal effects of *C* mode is better than *B* mode, this is mainly because the aerobic reaction time of *C* mode is longer, it can obtain better nitrification effects, nitrification is the prerequisite for denitrification, good nitrification can reduce the content of ON and NH_3-N in effluent, and it can provide the necessary substrate concentration of NO_x-N

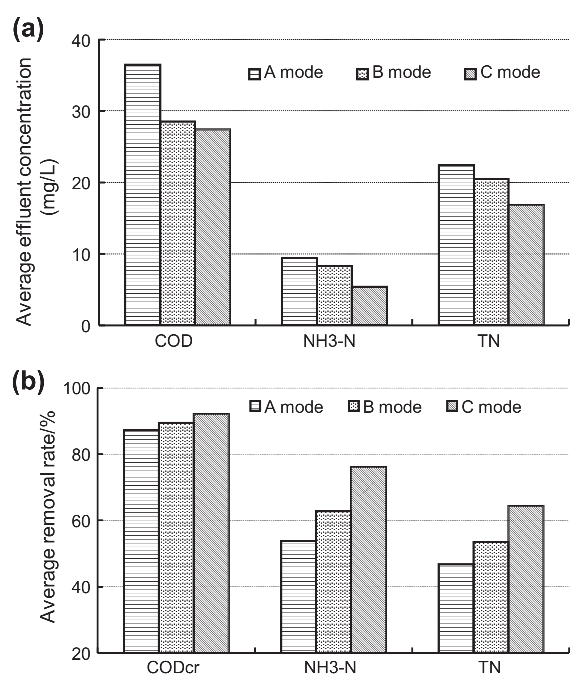

Fig. 6. (a) Average effluent concentration and (b) average removal rate of CODcr, NH_3-N, and TN under three different low-temperature operating modes.

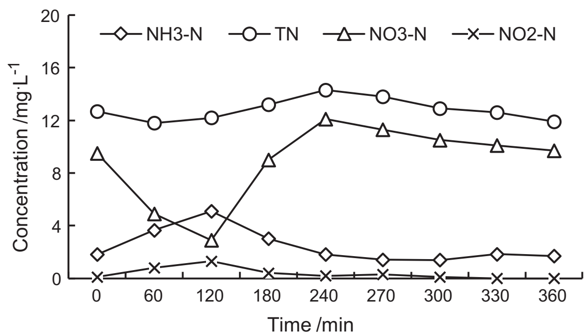

Fig. 7. Temporal variations of nitrogen conformation within one operation cycle under *C* operating mode.

(NO_3-N: nitrate-nitrogen and NO_2-N: nitrite-nitrogen) for denitrification.

3.1.4. Determination of low-temperature preferred operation mode

By the comparison of the three operational modes, the average effluent concentration and the average removal rate in each mode are respectively shown in Fig. 6(a) and (b). It is indicated from the results of this study that the removal efficiency of the *C* mode is better than *A* and *B* modes, the CAST system can achieve good performance on nitrogen removal operated in the *C* mode. The effluent concentration of the CODcr under the *C* operating mode is 17.9–36.7 mg/L, with an average of 27.4 mg/L, the average removal rate is 91.83%. The effluent ammonia concentration is 4.2–6.9 mg/L, with an average of 5.4 mg/L, the average removal rate is 75.6%; the effluent TN concentration is 14.2–18.9 mg/L, with an average of 17.2 mg/L, the average removal rate is 62.9%. The effluent indexes can all steadily reach the "National first level *B* criteria" of the "Discharge standard of pollutants for municipal wastewater treatment plant" (GB18918-2002). Therefore, *C* operation mode was chosen as the preferred operation mode under low-temperature and high-load conditions in WWTP.

3.2. Analysis of nitrogen conformation variations under the optimal mode

The optimized results indicated that TN removal performance of *C* mode was better than *A* and *B* modes, there were mainly the following reasons: (1) *C* mode used the rundle and semi-restricted aeration, the aeration process was divided into two stages, last half an hour at influent phase was the stage of micro aeration, DO was maintained below 1.0 mg/L at all times. At this stage, the low DO concentration was a benefit for forming macro-environment of local anoxic/anaerobic in the biochemical pool and for forming micro-environment of anoxic/aerobic in the interior and exterior of zoogloea [31–33], it strengthened the role of simultaneous nitrification and denitrification (SND). Generally, the most common way to remove nitrogen from wastewater is the combination of two sequential biological processes: autotrophic nitrification and heterotrophic denitrification. The first step is performed by two different bacterial populations and involves the oxidation of ammonia to nitrite by ammonia-oxidizing bacteria and the subsequent oxidation of nitrite to nitrate by nitrite-oxidizing bacteria. The second is a process performed by a wide variety of micro-organisms and involves the reduction of nitrate to nitrite and finally to gaseous elemental N_2 anoxically, using organic material as electron donor [34]. The SND process represents a significant advantage over the separated biological nitrogen removal processes, so the residual NO_x-N in previous cycle and produces in this cycle were removed efficiently. (2) Low DO concentration could also help to slow down aerobic consumption rate of the carbon source substances at the micro aeration stage in the system, the high carbon source of influent was used for denitrification, it partially alleviated the problem of insufficient carbon source for denitrification. (3) The DO control increased 2–4 mg/L at the latter 2 h of normal aeration phase, this approach can guarantee the normal progress of nitrification reaction and make DO concentration decrease rapidly at the settling stage, the aim is to put up sequential denitrification. Fig. 7 is the variation of nitrogen conformation within one operation cycle under *C* operating mode.

Fig. 7 demonstrates that the variation of different nitrogen forms was diverse in an operating cycle with the changes of DO concentration. At no- and micro-aeration stages, the denitrifying bacteria made full use of easily degradable organic matter such as volatile fatty acids and alcohols in water as carbon source for denitrification quickly, Nitrate-Nitrogen (NO_3-N) in biological pool declined significantly. Then, the lower DO concentration limited the nitrification reaction, it made the nitrification rate of the system less than the ammonification rate, the NH_3-N concentration of biochemical pool began to rise and reached the peak value before the end of micro aeration stage. After entering into the main aeration stage, the DO concentration of biochemical pools rose to above 2.0 mg/L rapidly, the appropriate DO concentration accelerated the rate of nitrification, the NH_3-N accumulated during the previous phase and the new section in the biochemical pool were rapidly transformed into NO_3-N.

At this time, the denitrification was inhibited by high DO concentration, so NO_3-N produced by the nitrification reaction could not be reverted into Nitrogen (N_2), and it made the TN concentration in the system continue to rise until the coming peak before the end of the aeration. DO concentration within the biological pool decreased rapidly after the aeration over, while denitrifying bacteria used endogenous carbon within the microbial body for denitrification, the concentrations of NO_3-N and TN in the system decreased gradually.

3.3. Parameter optimization under the optimal operating mode

DO and MLSS concentration in the aeration phase are both important parameters affecting the pollutant removal performance, so they were selected as the optimized parameters one by one on the basis of the preferred *C* operating mode.

3.3.1. The optimum control of DO concentration

DO is one of the main factors affecting the removal efficiency of the CAST process, the appropriate DO concentration is of great significance for the operating performance and energy saving in wastewater treatment plant. The optimization period of DO was selected in February 2008. DO concentration was respectively operated at three-levels of 1.0–2.0, 2.0–3.0, and 3.0–4.0 mg/L in the aeration phase (Fig. 8 and Table 6). It required continuous monitoring of 5–8 days after one-day stable operation in each level, and the taking samples were set as four cycles per day (6 h per cycle), the representative data of 10 groups for each gradient were selected as the samples to contrastively analyze. As DO had a certain degree of fluctuations with the water level and water quality at the aeration stage, DO in this study represented the average value at the aeration stage. The rest parameters were basically same as designs, where sludge concentration was at 3,500–4,500 mg/L, water filling ratio was from 0.2 to 0.28, and water temperature was at 12–18℃.

Fig. 8(a) indicates that CODcr removal effects under the three-level DO conditions were relatively stable, the average effluent concentration was respectively 32.1, 28.0, and 23.3 mg/L, through the analysis of the removal rate, the removal rate of CODcr improved with the increase of DO concentration, the average removal rate of CODcr reached the maximum value of 92.3% when DO concentration was at 3.0–4.0 mg/L, while the average removal rate was the minimum value of 88.5% when DO concentration was at 1.0–2.0 mg/L. Results reflected in this test were

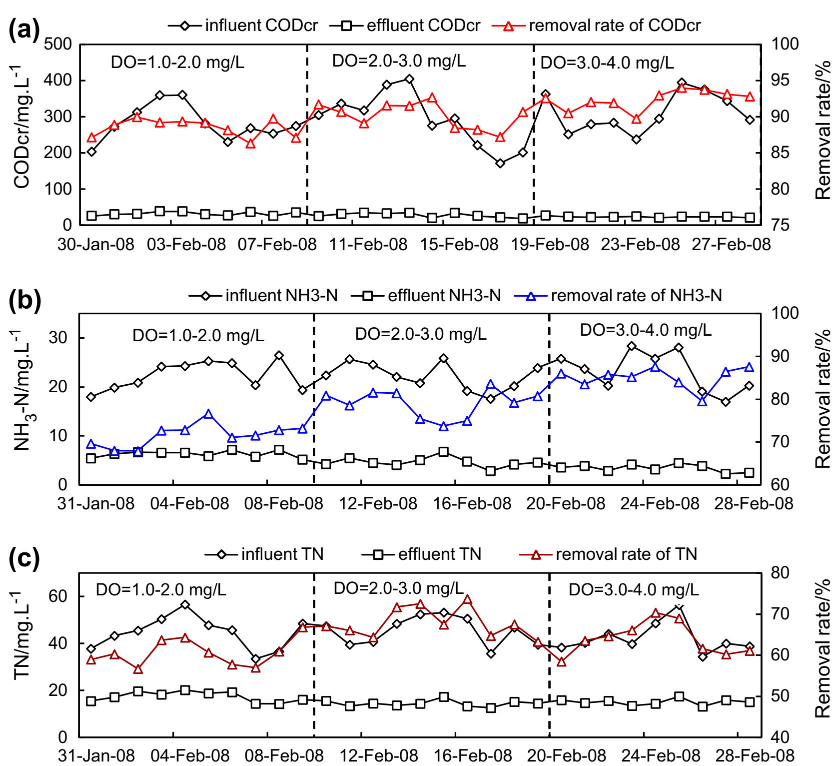

Fig. 8. (a) CODcr, (b) NH_3-N, and (c) TN removal performance under conditions of different DO levels.

Table 6
CODcr, NH_3-N, and TN removal performance under the condition of different DO levels

DO (mg/L)	Date (D/M/Y)	Influent (mg/L)			Effluent (mg/L)			Removal rate (%)		
		CODcr	NH_3-N	TN	CODcr	NH_3-N	TN	CODcr	NH_3-N	TN
1–2	30/01/08	203	18.0	37.8	26.1	5.5	15.5	87.1	69.7	59.0
	31/01/08	272	19.9	43.3	30.3	6.4	17.2	88.9	68.0	60.3
	01/02/08	312	20.9	45.5	31.4	6.7	19.7	89.9	67.9	56.7
	02/02/08	359	24.2	50.4	38.8	6.6	18.3	89.2	72.7	63.7
	03/02/08	360	24.3	56.6	38.4	6.6	20.2	89.3	72.8	64.3
	04/02/08	281	25.3	47.8	30.5	5.9	18.8	89.1	76.7	60.7
	05/02/08	230	24.9	45.7	27.3	7.2	19.3	88.1	71.1	57.8
	06/02/08	268	20.4	33.5	36.7	5.8	14.4	86.3	71.6	57.0
	07/02/08	253	26.5	36.6	26.0	7.2	14.3	89.7	72.8	60.9
	08/02/08	274	19.4	48.5	35.4	5.2	16.1	87.1	73.2	66.8
	Average	281	22.4	44.6	32.1	6.3	17.4	88.5	71.7	60.7
2–3	09/02/08	304	22.4	47.4	25.3	4.3	15.6	91.7	80.9	67.1
	10/02/08	336	25.7	39.5	31.4	5.5	13.4	90.7	78.6	66.1
	11/02/08	317	24.6	40.7	34.6	4.5	14.5	89.1	81.6	64.4
	12/02/08	388	22.1	48.4	32.8	4.1	13.7	91.5	81.4	71.7
	13/02/08	404	20.8	52.4	34.4	5.1	14.4	91.5	75.5	72.5
	14/02/08	275	25.9	53.2	20.2	6.8	17.3	92.7	73.7	67.5
	15/02/08	295	19.2	50.6	34.1	4.8	13.3	88.4	75.0	73.7
	16/02/08	221	17.6	35.7	26.1	2.9	12.6	88.2	83.6	64.7
	17/02/08	171	20.2	46.8	21.9	4.2	15.2	87.2	79.2	67.5
	18/02/08	201	23.9	39.5	18.8	4.6	14.5	90.6	80.8	63.3
	Average	291	22.2	45.4	28.0	4.7	14.5	90.2	79.0	67.9
3–4	19/02/08	362	25.8	38.3	27.0	3.6	15.9	92.5	86.0	58.5
	20/02/08	251	23.7	40.3	23.9	3.9	14.7	90.5	83.5	63.5
	21/02/08	279	20.3	44.1	22.3	2.9	15.6	92.0	85.8	64.6
	22/02/08	283	28.4	39.8	23.0	4.2	13.5	91.9	85.2	66.1
	23/02/08	237	25.8	48.6	24.4	3.2	14.4	89.7	87.6	70.4
	24/02/08	294	28.1	56.4	20.8	4.5	17.5	92.9	84.0	69.0
	25/02/08	394	19.1	34.4	23.7	3.9	13.2	94.0	79.6	61.6
	26/02/08	375	17.0	40.0	23.6	2.3	15.9	93.7	86.5	60.3
	27/02/08	343	20.3	38.8	23.6	2.5	15.1	93.1	87.6	61.1
	28/02/08	291	21.9	46.7	21.0	2.7	16.2	92.8	87.7	65.3
	Average	311	23.0	42.7	23.3	3.4	15.2	92.3	85.4	64.0

consistent with the theory: the higher the DO concentration was (at a reasonable range), the greater the rate of microbial degradation was, and the corresponding CODcr removal effects was good.

The impacts of DO on the removal efficiency of NH_3-N were great. NH_3-N removal rate went up with the increase of DO concentration (Fig. 8(b)), when DO concentration reached 3.0–4.0 mg/L, NH_3-N removal efficiency reached the highest, the average removal rate was 85.35%, it was 6.4 and 13.6% higher than the efficiency of DO = 2.0–3.0 and 1.0–2.0 mg/L, respectively. When the DO concentration was 1.0–2.0 mg/L, NH_3-N effluent concentration increased significantly, and it was close to the upper limit of effluent, there would appear water quality fluctuations under this DO concentration, the situation of excessive water quality standard would appear frequently, so DO concentration should not be less than 2.0 mg/L in operation.

The changing trends of TN removal rate with the DO concentration first increased and then decreased (Fig. 8(c)), the best TN removal effects was 2.0–3.0 mg/L DO level, the average removal rate reached 67.9%, it was respectively 7.2 and 4.3% higher than DO = 1.0–2.0 and 3.0–4.0 mg/L. Why the average removal rate of TN at 3.0–4.0 mg/L DO level did not reach the highest value? The reasons were as follows: (1) SND of CAST process was the main form of nitrogen removal [35], when DO concentration was too high, the formation of aerobic/anoxic micro-environment was not easy within the sludge floc body, thus it affected the denitrification process. (2) ammonia oxidation would be limited when DO concentration was too low, and the substrate concentration for denitrification was innutritive, which would affect the nitrogen removal effects. Therefore, the impacts of DO concentration on CODcr removal were small, but the impacts of DO concentration on nitrogen removal performance were obvious. It could be seen from the results that CODcr and NH_3-N effluent effects enhanced with the increase of DO concentration, when DO concentration was higher than 2.0 mg/L, it could guarantee the stability of the effluent, TN removal effects reached the peak value at 2.0–3.0 mg/L. In practice, in the case of ensuring the compliance of pollutants removal rate, it was not necessary blindly to pursue high removal efficiency of CODcr, NH_3-N, and other pollutants in production, we should not only improve the final nitrogen removal performance but also achieve the objective of energy saving through the reasonable control of DO. Therefore, the DO concentration maintained at 2.0–3.0 mg/L at the aeration stage was reasonable in terms of the actual operation situation of WWTP in winter.

3.3.2. The optimum control of MLSS concentration

The optimum control of MLSS concentration in March was conducted on the basis of the optimal DO value. MLSS value is also one of the important parameters of activated sludge treatment system, MLSS control is considered as an important factor for the nitrogen removal [36]. It directly affects the operation performance and stability. During the test, the MLSS values were respectively controlled in level-levels of 3,000–4,000, 4,000–5,000, and 5,000–6,000 mg/L (Fig. 9 and Table 7). Because the sludge concentration (concentration of main reaction zone at 10 min before the end of aeration unless specification in this study) would vary with water level within the cycle, MLSS was controlled at a different gradient during the study period, the rest parameters was also basically same as designs, DO was determined at 2.0–3.0 mg/L in the aerobic phase, water filling ratio was from 0.20 to 0.28, water temperature was at 14℃–20℃.

Fig. 9 shows that changes of MLSS concentration had obvious affects on CODcr removal, the average removal rates of CODcr under the condition of three-level MLSS concentrations were respectively 89.3, 90.9, and 90.3%. Table 7 indicates that the sludge concentration (in reasonable extent) was closely related to the CODcr load, and the degradation of organic matter was more plenitude, so the CODcr removal effects were improved by the reasonable increase of MLSS concentration. The average removal rate of NH_3-N was rising with the increase of MLSS concentration, the average removal rate of NH_3-N under three

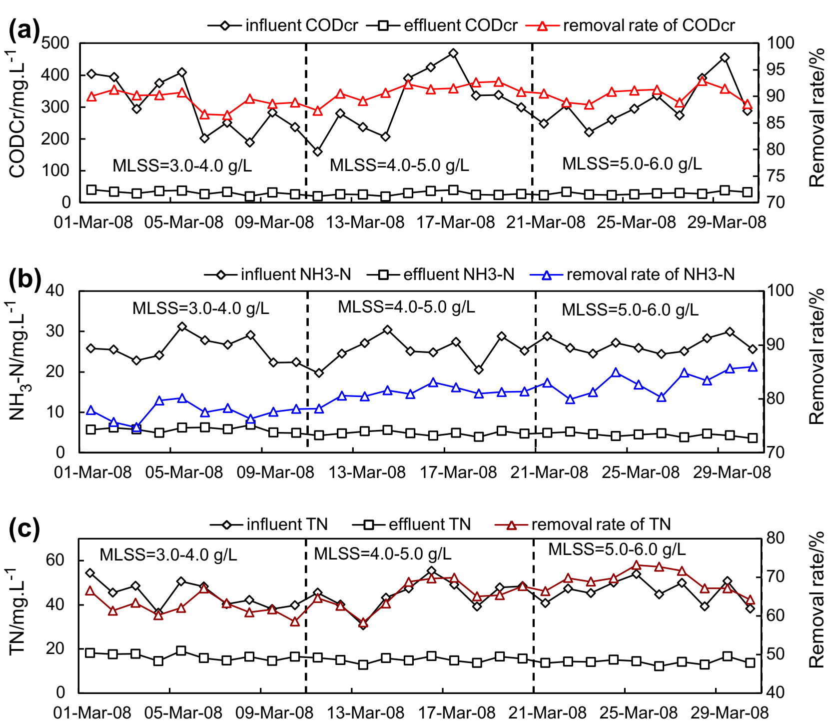

Fig. 9. (a) CODcr, (b) NH_3-N, and (c) TN removal performance under conditions of different MLSS levels.

Table 7
CODcr, NH_3-N, and TN removal performance under the condition of different MLSS levels

MLSS (mg/L)	Date (D/M/Y)	Influent (mg/L)			Effluent (mg/L)			Removal rate %		
		CODcr	NH_3-N	TN	CODcr	NH_3-N	TN	CODcr	NH_3-N	TN
3,000–4,000	01/03/08	404	25.8	54.4	40.4	5.7	18.2	90.0	77.9	66.5
	02/03/08	394	25.5	45.5	34.4	6.2	17.6	91.3	75.7	61.3
	03/03/08	294	22.8	48.6	28.8	5.8	17.8	90.2	74.7	63.4
	04/03/08	375	24.1	36.4	36.6	4.9	14.5	90.2	79.7	60.2
	05/03/08	409	31.2	50.6	37.8	6.2	19.2	90.8	80.1	62.1
	06/03/08	202	27.8	48.3	27.0	6.3	15.9	86.6	77.5	67.1
	07/03/08	251	26.7	40.3	33.9	5.8	14.8	86.5	78.3	63.3
	08/03/08	189	29.1	42.2	19.7	6.9	16.5	89.6	76.3	60.9
	09/03/08	283	22.3	38.1	32.2	5.0	14.6	88.6	77.6	61.7
	10/03/08	237	22.4	39.8	26.4	4.9	16.5	88.9	78.1	58.5
	Average	304	25.8	44.4	31.7	5.8	16.6	89.3	77.6	62.5
4,000–5,000	11/03/08	160	19.7	45.5	20.3	4.3	16.1	87.3	78.2	64.6
	12/03/08	280	24.5	40.1	26.5	4.8	15.0	90.5	80.6	62.6
	13/03/08	237	27.1	30.7	25.7	5.3	12.8	89.2	80.4	58.3
	14/03/08	207	30.4	43.2	19.3	5.6	15.9	90.7	81.6	63.2
	15/03/08	390	25.1	47.4	30.1	4.8	14.8	92.3	80.9	68.8
	16/03/08	425	24.8	55.4	36.8	4.2	16.8	91.3	83.1	69.7
	17/03/08	469	27.4	49.1	39.8	4.9	14.8	91.5	82.1	69.9
	18/03/08	336	20.5	39.2	24.7	3.9	13.7	92.6	81.0	65.1
	19/03/08	338	28.8	47.9	24.5	5.4	16.6	92.8	81.3	65.4
	20/03/08	299	25.2	48.5	27.3	4.7	15.7	90.9	81.3	67.7
	Average	314	25.4	44.7	27.5	4.8	15.2	90.9	81.1	65.5
5,000–6,000	21/03/08	248	28.8	40.8	23.5	4.9	13.7	90.5	83.0	66.4
	22/03/08	306	25.9	47.4	34.1	5.2	14.3	88.9	79.9	69.8
	23/03/08	221	24.5	45.3	25.5	4.6	14.1	88.5	81.2	68.9
	24/03/08	260	27.2	50.0	23.7	4.1	15.2	90.9	84.9	69.7
	25/03/08	295	25.9	53.9	26.2	4.5	14.5	91.1	82.6	73.2
	26/03/08	336	24.4	44.7	29.4	4.8	12.2	91.3	80.3	72.7
	27/03/08	274	25.1	49.9	30.5	3.8	14.2	88.9	84.9	71.6
	28/03/08	391	28.3	39.3	27.7	4.7	12.9	92.9	83.4	67.1
	29/03/08	455	29.9	50.8	38.9	4.3	16.7	91.5	85.6	67.1
	30/03/08	288	25.6	38.3	32.9	3.6	13.7	88.6	85.9	64.2
	Average	307	26.6	46.0	29.2	4.5	14.2	90.3	83.2	69.1

concentration gradients were 77.6, 81.1, and 83.2% respectively. The following were the main reasons: firstly, high sludge concentration meant the increase of the total amount of micro-organism in the activated sludge, it would help reduce the nitrogen load, then it would result in high nitrification effects; secondly, the rising of the sludge concentration could increase the sludge age of the system, it would create favorable conditions for the growth of nitrification bacteria with long generation period and increase total amount and proportion in the microbial community, and thus the nitrification performance of the system was enhanced. Changes of the sludge concentration had great impacts on TN removal efficiency, the denitrification effects enhanced with the increase of MLSS concentration, the TN removal rates were respectively 62.5, 65.5, and 69.1% under three-level concentration gradients.

On all accounts, alternating operation condition is indispensable for nitrogen removal in municipal wastewater, this results are consistent with the previous study [37,38]. The following are the main reasons for the results: firstly, the diameter of micro-organism bacterial micelles under the high sludge concentration is relatively large, the inside of bacterial micelles more easily forms the aerobic/anoxic micro-environment to improve the occurrence of SND, and nitrogen removal effects [39–41]. Secondly, under the condition of the high sludge concentration, it can make better use of the organic matter which is more difficult to be degraded to carbon source of denitrification, this is particularly important for nitrogen and phosphorus removal process, especially for the situations of carbon shortage [42,43]. Thirdly, the denitrification performance of the system decreases because the activity of denitrifying bacteria weakens at low temperature. By increasing the sludge concentration, it can make the amount of denitrifying bacteria in the system increase, and reduce the nitrogen load within the system, and then ensure the denitrification performance. According to the study of this stage, sludge concentration (MLSS) of WWTP should be maintained at 5,000–6,000 mg/L in winter, the corresponding sludge age is at 24–28 d, it is longer than 18d of the designed sludge age. Besides, as the wastewater plant uses biological phosphorus removal supplemented by the chemical method, it need not consider the impacts of the system on phosphorus removal performance due to the increase of SRT.

4. Conclusions

The optimization study about three different low-temperature operating modes was investigated in order to solve the existing problems of poor nitrogen removal efficiency during low-temperature period in WWTP. The results indicated that the CAST was a very flexible tool and was particularly suitable for the treatment of municipal wastewater, characterized by low-temperature condition and by frequent changes in pollutants load. Based on the tested results of the study following major conclusions were drawn:

(1) The changing of CAST operation mode can achieve a steady discharge and high nitrogen removal efficiency under low-temperature and high-load conditions. *C* mode [influent 2 h, aeration 2.5 h (aeration starting from 1.5 h after influent), settling 1 h, decant/idle 1 h] was identified as the preferred operation mode in WWTP under the low-temperature and high-load conditions. The average removal rates of CODcr, NH_3-N, and TN at the preferred mode were 91.8, 75.6, and 62.9% respectively.

(2) The DO level and MLSS content are important factors impacting the removal of CODcr, NH_3-N, and TN. Under the low-temperature and high-load conditions and using *C* mode operation the best range for DO was 2.0–3.0 mg/L and for MLSS was 5,000–6,000 mg/L. Under these conditions the average removal rates of CODcr, NH_3-N, and TN were 90.3, 83.2, and 69.1%, respectively.

(3) A suitable operation mode and use of the best range for the control parameters DO and MLSS could act as an enhancement strategy for nitrogen removal under low-temperature and high-load conditions. The data obtained in this study would show: best operation mode was 2 h of influent, 2.5 h of aeration (aeration starting from 1.5 h after influent), 1 h of settling, 1 h of draw/idle, and optimum ranges for DO and MLSS were 2.0–3.0 mg/L and 5,000–6,000 mg/L, respectively. These data are of direct practical value in the management of a wastewater treatment plant and it is an effective strategy for enhancing the effects of nitrogen removal.

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